Calculation of Power Density of the PEBB1.5 based ARCP Electrical Power Converter

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Abstract

This report documents the power density calculation of a PEBB-based electrical power converter. The converter was developed under the Power Electronic Building Block Program sponsored by the Office of Naval Research. Because of the S&T nature of the effort and the associated focus on proof of concept demonstration rather than packaging engineering, several methods of calculating the power density of the unit are presented, starting with an as-built method and projecting toward what one can reasonably conclude is reachable through logical optimization of how the equipment is assembled. The as-built power density of the converter is around 8kW/cubic ft. The projected power density, given some realistic assumptions, can approach 65kW/cubic ft. In addition, the phaseleg sub-assembly of the unit, which can be considered the main power (and heat) producer of the converter, has a power density of 120kW/cubic ft. at the present operating power output of 200kW. It is projected that the unit can operate up to 250kW, which would push the phaseleg power density beyond 150kW/cubic ft.

Background

The Naval Surface Warfare Center has designed and built an electrical power converter using PEBB1.5 core devices and employing them in an auxiliary resonant commutated pole (ARCP) zero voltage turn-on circuit topology. This S&T project had a design goal of achieving 250kW of output power in the 95% efficiency range. To date the unit has been demonstrated up to 200kW. Work is proceeding to reach our 250kW goal. The purpose of this report is to provide documentation as to the power density of the unit as it presently exists and to project it to the 250kW goal. The focus of this S&T demonstrator was not to optimize the packaging of the unit for maximum power density; rather it was meant to demonstrate the concept of applying PEBB technology for use as a multi-functional power converter. The unit was built with ease of instrumentation and repair in mind. It is assumed that significant engineering will be required to optimally package the unit for both commercial and military environments. Three methods of calculating this power density are presented, each with a best case and a worst case value. The reader is welcome to select the preferred method of calculation for drawing his/her own conclusions.

Figure 1 - PEBB1.5 High Power Demo Cabinet, front view

Volume Calculation Method #1 – As Built

The PEBB1.5 High Power Demonstrator was built into a standard 24" rack mount enclosure. This enclosure provided ample room for installing the inverter sub-assemblies, thermal management piping and in-

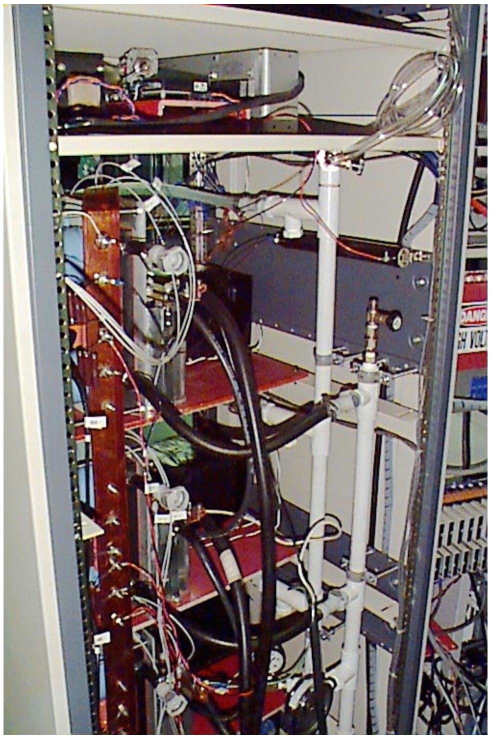


Figure 2 - PEBB1.5 High Power Demo Cabinet, rear view

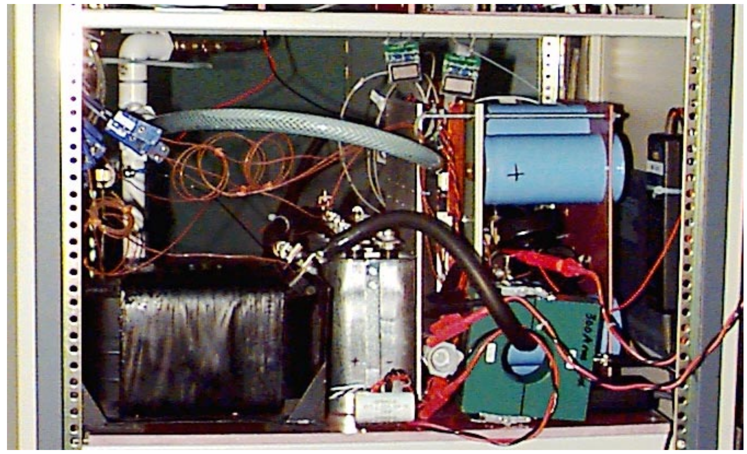


Figure 3 - Close-up of Phaseleg/Output Filter Rack, front view

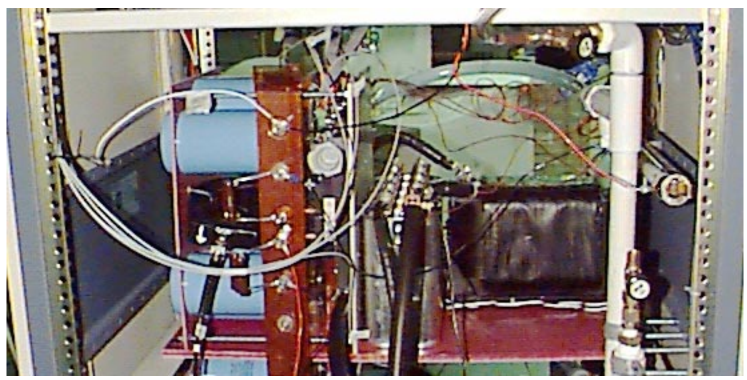


Figure 4 - Close-up of Phaseleg/Output Filter Rack, rear view

strumentation. Figures 1 through 4 show the overall cabinet from the front and rear as well as close up views showing unused space inside. Interfaces to the cabinet include:

- DC electrical power input connections
- 3-phase AC electrical output connections
- Cooling water inlet and outlet connections (1gal/min/phaseleg 60 deg. F)
- 110Vac for gate drive and sensor power
- 12 gate drive optical signal fibers
- A pair of DC input voltage sensor feedback signal leads
- 3 pairs of output load current feedback signal leads

In the present implementation, the controller was located in a separate enclosure in order to minimize electromagnetic interference and compatibility issues, which the program was not ready to undertake at the present time. Follow-on efforts will incorporate the controller into the power cabinet, removing a large number of the interfaces to the cabinet.

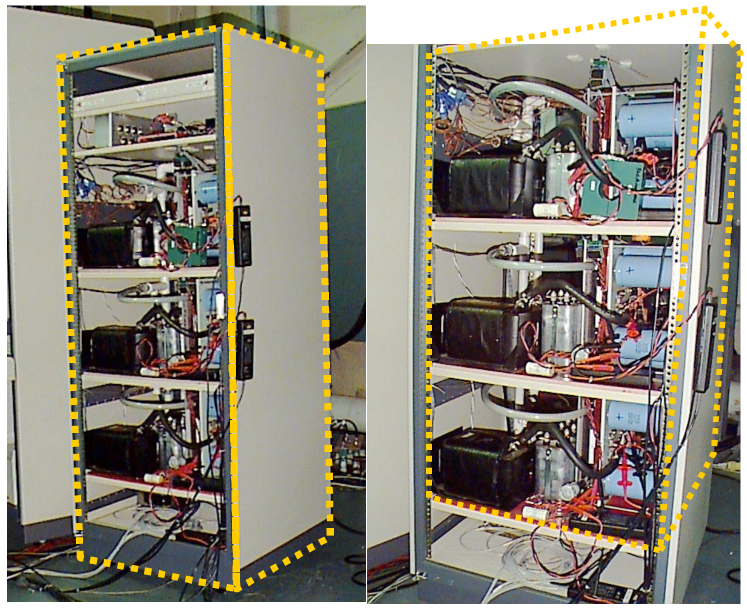
From the photos, it can be seen that the inverter resides almost entirely on the three middle racks of the cabinet. Volume Calculation Method #1 will be considered as the as-built volume calculation of the unit. It will assume as a worst case volume the entire 24” rack cabinet and as a best case volume the three middle racks (see Figures 5 and 6). Table 1 shows the results of the calculations, which summarize as 28 cubic feet worst case and 16.75 cubic feet best case.

Volume Calculation of PEBB1.5 ARCP Inverter Using Existing Enclosure					
Calculation Method #1					
Defined Area	Width (inches)	Depth (inches)	Height (inches)	Volume (Cubic In.)	Volume (Cubic Ft.)
Entire Cabinet (Worst Case)	27.25	25.25	70.50	48508	28.07
Working Volume of Phaselegs and Output Filter (Best Case)	24.00	24.00	50.25	28944	16.75

Table 1 - Worst and Best Case Volume Calculations Using Method #1

Volume Calculation Method #2 – Sub-Assembly Arrangement Optimization

Upon review of the previous photos, significant amounts of empty space were included in the volume calculations. Follow-on calculations will assume that improvements can be made to minimize this empty space. Calculation Method #2 breaks the inverter into sub-assemblies which, if attention is applied to their arrangement, one can logically conclude the inverter would fit into these smaller calculated volumes.

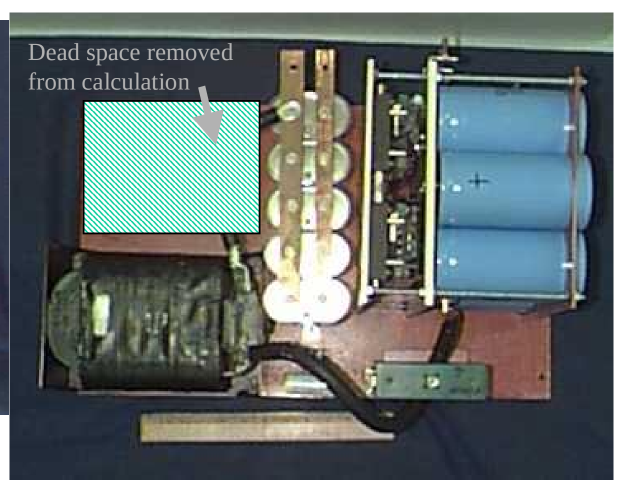


Figures 5 + 6 - Worst Case and Best Case Volume Envelopes

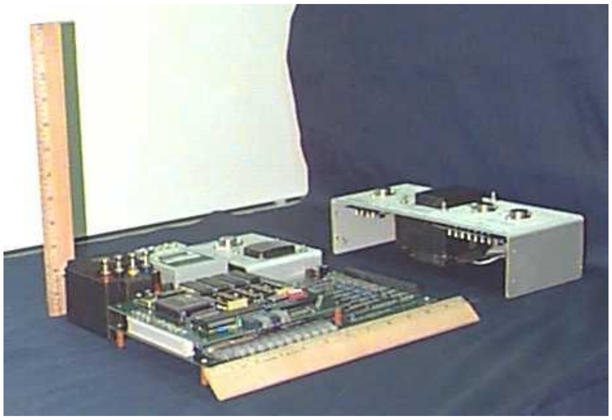
In Calculation Method #2, the PEBB1.5 Demonstrator is divided into 2 subassemblies:

1. Qty of 3 ARCP Phaselegs with DC bus capacitors, output filter and current sensor (Figures 7+8)
2. Qty of 1 Controller/Gate drive assembly with voltage sensors and power supplies for each (Figures 9+10)

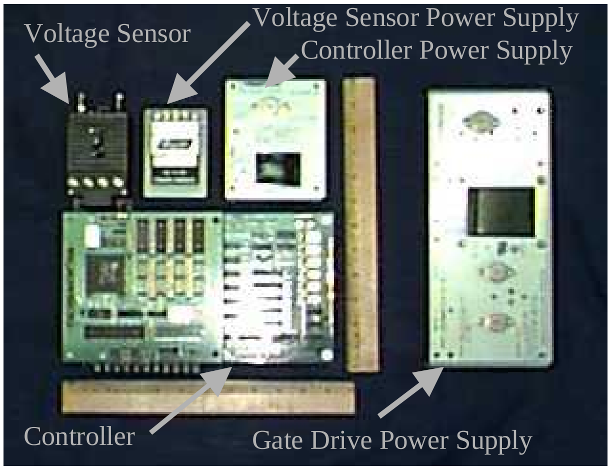
In this case, the volume envelope is optimized somewhat over the previous calculation by not allowing so much vertical spacing between each phaseleg assembly. The envelopes included in these volume calculations are shown in Figures 11 and 12. The difference between the worst case envelope and the best case is in the elimination of some dead space volume behind the output filter inductor (refer back to Figure 8).



Figures 7 + 8 - Phaseleg, DC Bus Caps, Output Filter and Current Sensor



Figures 9 + 10 - Controller, Controller Supply, Voltage Sensor, Sensor Supply and Gate Drive Supply



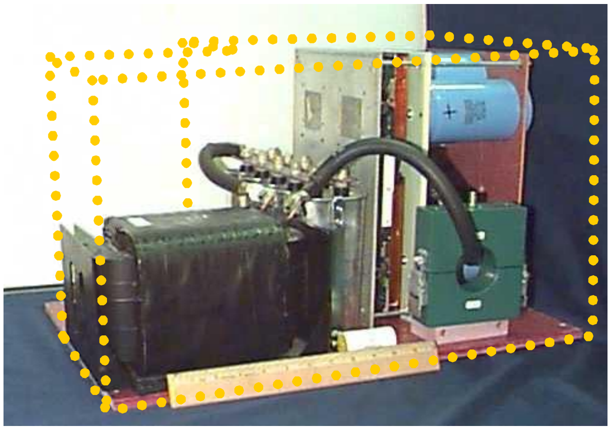


Figure 11- Phaseleg, DC Bus Caps, Output Filter and Current Sensor Envelope

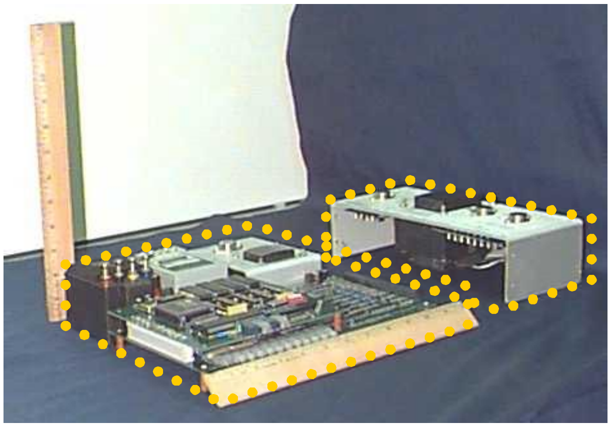


Figure 12 - Controller, Gate Drive Supply Envelope

Table 2 shows the results of the calculations, which can be summarized as 8 cubic feet worst case and 6.5 cubic feet best case.

Volume Calculations of PEBB1.5 ARCP Inverter Using Major Sub-Assemblies											
Calculation Method #2											
	Qty	Width each (In.)	Depth each (In.)	Height each (In.)	Gross Vol. (Cu. In. / Assy.)	Total Gross Vol. (Cu. In.)	Total Gross Vol. (Cu. Ft.)	Dead Space Vol. (Cu. In.)	Net Vol. (Cu. In.)	Total Net Vol (Cu. In.)	Total Net Vol. (Cu. Ft.)
DC Bus Cap, Phaseleg and Output Filter Sub Assembly	3	24	14	13	4368	13104	7.58	819	3549	10647	6.16
Controller w/Voltage Sensor	1	11	12	3	396	396	0.23	0	396	396	0.23
Gate Drive Power Supply	1	5	11	3	165	165	0.10	0	165	165	0.10
Worst and Best Case Volume							7.91				6.49

Table 2 - Worst and Best Case Volume Calculations Using Method #2

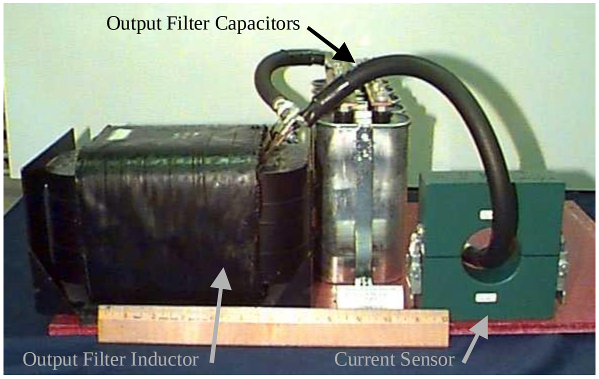


Figure 13- Output Filter and Current Sensor Envelope

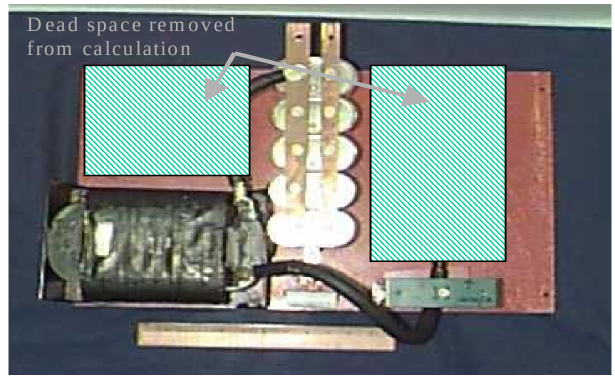


Figure 14 - Output Filter and Current Sensor, Top View

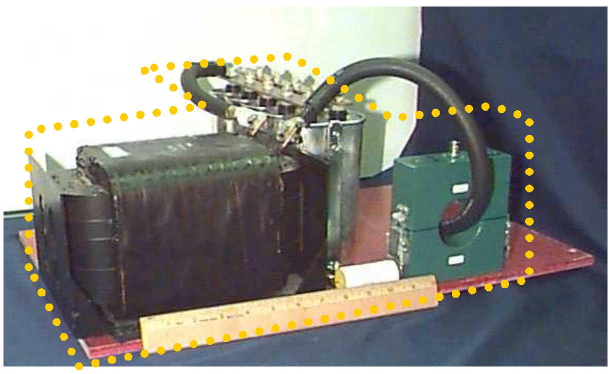


Figure 15- Output Filter Envelope

Figure 16 - Phaseleg envelope

Volume Calculation Method #3 – Sub-Assembly Parts Arrangement Optimization

It can be noted in Figure 11 that there is still a large amount of dead volume above the filter inductor and capacitors that is included in Calculation Method #2. Calculation Method #3 breaks the Phaseleg and output filter into separate subassemblies in an attempt to remove this dead volume from the calculations. The Controller and Gate Drive envelopes are kept the same as they were in the previous calculation. Figure 13 and 14 show the Output Filter and Current Sensor sub-assembly. Figure 15 shows the calculated envelope. Figure 16 shows the phaseleg as a separate volume. Table 3 shows the results of worst case (including dead space) and best case (removing dead space) volume calculations, which can be summarized as 5.5 and 3.8 cubic feet respectively.

Volume Calculations of PEBB1.5 ARCP Inverter Using Major Sub-Assemblies

Calculation Method #3

	Qty	Width each (In.)	Depth each (In.)	Height each (In.)	Gross Vol. (Cu. In. / Assy.)	Total Gross Vol. (Cu. In.)	Total Gross Vol. (Cu. Ft.)	Dead Space Vol.	Net Vol. (Cu. In.)	Total Net Vol (Cu. In.)	Total Net Vol. (Cu. Ft.)
ARCP Phaseleg w/DC Bus Capacitors	3	13	9	8	936	2808	1.63	0	936	2808	1.63
Output Filter w/Current Sensor	3	18	14	8	2016	6048	3.50	936	1080	3240	1.88
Controller w/Voltage Sensor	1	11	12	3	396	396	0.23	0	396	396	0.23
Gate Drive Power Supply	1	5	11	3	165	165	0.10	0	165	165	0.10
Worst and Best Case Volume							5.45				3.82

Table 3 - Worst and Best Case Volume Calculations Using Method #3

Phaseleg Volume Calculation

A final calculation was performed on the phaseleg assembly alone to determine the power density of the main processor of electrical power and heat (Figure 17). This calculation removes control, gate drive power supply and output filter from the calculation to give a value of power density for the main power handling part of the circuit. The phaseleg assembly has dimensions of 13” wide x 9” deep x 8” high yielding a volume of about 0.54 cubic feet. Given that it provides one third of the power of the 3- phase unit, its power density can be shown to be around 123 kW/cubic ft at the present 200kW power range demonstrated. This projects up to 150kW/cubic ft. at the goal of 250kW of output power.

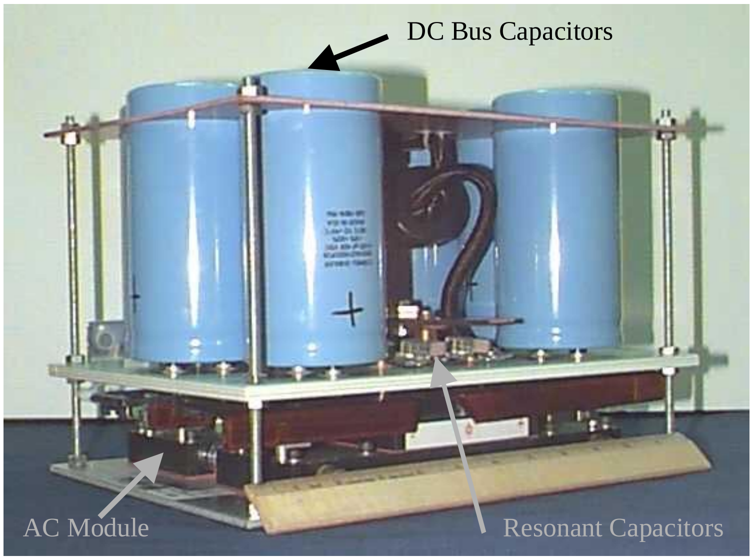


Figure 17 - ARCP Phaseleg Volume Envelope for calculation of phaseleg power density

Summary

Table 4 summarizes all 3 methods of calculating power density for the PEBB1.5 Demonstrator, plus the power density of the phaseleg alone. From this table, the PEBB-based power converter can be considered to have an as-built power density between 7 and 9 kW/cubic ft. However, with some reasonable assumptions in the optimization of the parts arrangement of the sub-assemblies and of the arrangement of the sub-assemblies themselves within the enclosure, the technology employed can be seen to approach 65kW/cubic ft. The 3 methods for calculating power density were discussed to allow an individual to draw their own conclusions as to what can be considered a reasonable projection of the performance of a proof of concept demonstrator to a fully militarized piece of equipment. Calculation Method #1 must be considered a very conservative calculation of achieved power density. Calculation Methods #2 and #3 represent a more reasonable assessment of power density when the conservatism of instrumentation and ease of repair is removed from the equation.

Power Density Summary of PEBB1.5 ARCP Demonstrator Using 200kW Present Accomplishments and 250kW Projected Design Goals

Calculation Method	Case	Volume (Cubic Ft.)	Present Power Density (kW/ Cubic Ft.)	Projected Power Density (kW/Cubic Ft.)
#1	Worst Case	28.07	7.12	8.91
	Best case	16.75	11.94	14.93
#2	Worst Case	7.91	25.29	31.61
	Best Case	6.49	30.84	38.54
#3	Worst Case	5.45	36.70	45.87
	Best case	3.82	52.29	65.37
	Single Phaseleg Assembly Alone	0.54	123.08	153.85

Table 4 - Summary of Present and Projected Power Densities